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Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect

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Abstract

Evidence for the proposed Anthropocene epoch in fluvial geomorphology hinges on the influence of human activities relative to natural forcing. However, research on cause-effect understanding in river channel evolution has rarely focused on the cumulative impact of multiple drivers for change, limiting insights. Systematic review of 25 recent studies professing to explain reach-scale channel responses to cumulative impacts of human activities and natural forcing over the recent past (ca. 1880-2005) reveals some consistencies in spatio-temporal response across various catchment sizes (median 3000 km^2) in mostly industrialized nations. Common drivers for change include changing flood and flow regimes, dam construction, changing land uses and forest cover, bank protection and instream aggregate mining. Recent channel evolution has predominantly involved narrowing, incision and terrace development, reduced bed sediment storage, lower activity rates and simplified channel geometries. Rates of channel change frequently peaked 1955-1990, providing some support for the Anthropocene 'Great Acceleration'. Evidence here suggests that many river systems are now in morphologically-novel configurations, coinciding temporally with dramatic recent declines in global freshwater aquatic biodiversity. Sustainable approaches to freshwater management must acknowledge these configurations, placing emphasis on process-based approaches to river ecosystem health in which sediment cascades are reconceived to reflect altered longitudinal and lateral connectivity. However, the reviewed studies are driven largely by expert judgment, depicting cause-effect associations through summary conceptual models based on spatial proximity and temporal synchronicity, providing insufficient scientific proof for the Anthropocene based on the 'overwhelming' impact of human factors. More conclusive cause-effect statements will require hypothetic-deductive approaches, explicit functional criteria and best-practice environmental model building. Geomorphologists should now move beyond the 'phase of discovery' and develop rigorous proofs for cause-effect relationships of cumulative impact; this may be enhanced by developing an avowedly 'Anthropocene' perspective in which rivers are viewed critically as socio-biophysical systems co-evolving with human activity.

Key words: fluvial geomorphology, drivers of change, cumulative impact, channel evolution, Anthropocene, river management

Highlights:

- Recent studies of cumulative impact in fluvial geomorphology are reviewed
- Rivers channels have typically narrowed, incised, simplified, reduced activity
- Rates of change peaked in the period 1955-1990
- Changes coincide with massive declines in aquatic biodiversity
- New approaches are required to rigorously establish cause-effect relationships

1. Introduction

Interest in the proposed Anthropocene epoch (Crutzen, 2002) has focused attention on the impact of human activities on global systems relative to their natural functioning. Debate hinges, in part, on the evidence for 'significant' human capacity for ecosystem engineering (Smith and Zerder, 2013) versus humans' 'overwhelming' impact on Earth systems (Steffen et al., 2007). It is further argued that the Earth's surface is now operating in a no-analogue state (i.e., outside the range of natural variability typical of recent geological time, Crutzen and Steffan, 2003), with rates of Earth system change so entirely dominated by human activity that other factors of the 'Anthropocene equation', such as astronomical forcing, geophysical forcing and the internal dynamics of the Earth system, are relatively inconsequential (Gaffney and Steffan, 2017). However, answers about the existence and starting point for the Anthropocene may be discipline specific (see Ruddiman, 2015), including in geomorphology (Brown et al., 2013).

Geomorphology research has long recognized the impact of human activities on fluvial landscapes (Marsh, 1864; Gilbert, 1917; Happ et al., 1940; Happ, 1944) with scientific programs dedicated to the topic since 1956 (Thomas, 1956; and see review by James and Marcus, 2006). By the late 1960s, as geomorphology adopted a reductionist paradigm but also began to concern itself with applied, practical problems (Church, 2010), a parallel track developed wherein studies into the equilibrium form of naturally-functioning river channels developed alongside seminal studies recognizing the impact of human action on the morphological evolution of rivers (e.g., Wolman, 1967; Leopold, 1968; Schumm, 1969). Subsequently, a wide variety of individual human activities were identified as affecting river channel evolution at various scales (e.g., Downs and Gregory, 2004, Table 4.3). Commonly cited examples include the impact of deforestation, urbanization, channelization, dam construction, in-stream mining, etc. The magnitude of impact on fluvial systems resulting from these actions is argued to depend upon the receiving catchment's relief, materials and susceptibility to tectonic activity (i.e., measures of available energy and resistance to erosion), with evidence for sustained Anthropocene impact being more discernible in small- to medium-sized catchments where sediment flux disruptions (i.e., supply variations) may be rapidly transmitted throughout the river system (Brown et al., 2017). However, impacts are likely to be almost ubiquitous in all river systems (Wohl, 2001, 2013), with implications for both how we study and manage river systems (Wohl, 2019).

Functionally, human activities, along with natural influences such as flood events and climate trends, represent *drivers for change* in fluvial geomorphology, forcing factors that can cause changes in attributes of the river channel morphology such as width, depth, sinuosity, channel pattern, etc. (termed 'modes of self-adjustment', Maddock, 1970, or 'degrees of freedom', Lane, 1955; Hey, 1982, 1997). Such *responses* of river channel morphology to drivers of change have been characterized in various ways including the enduring conceptual system of Schumm (1969) that ascribes qualitative change in response variables to increases or decreases in water and sediment discharge related to specific human actions. Analytically, approaches ranging from regression-based statistics to process-based models have been used to associate causal drivers with their morphological effect. At the core of such approaches is an attempt to understand geomorphological *sensitivity* to change (Schumm, 1985, 1991, Fryirs, 2017).

Fundamentally, sensitivity describes a ratio between the magnitude of change in one or more of the channel's degrees of freedom and the magnitude of change in the driver(s) causing that adjustment (Downs and Gregory, 1995), but it also includes temporal factors related to the persistence of the morphological response (Brunsden and Thornes, 1979), resulting in multiple perspectives (Downs and Gregory, 2004). Deriving quantitative expressions for geomorphological sensitivity has long been recognized as complex (e.g., Bull, 1979), as it involves combining *spatial* factors related to variable hydrology and sediment regimes inherited from natural hydroclimatic and lithostratigraphic process domains (Montgomery, 1999) with those caused by human activities, and *temporal* attributes related to natural inheritance from the Holocene's changing climate and legacies resulting from multiple human actions.

Advancing cause-and-effect-based knowledge about the morphological responsiveness of river channels to natural and human drivers of change has value in evaluating the relative influence of human activity on river systems and thus defining a fluvial geomorphological perspective on the Anthropocene. This knowledge has multiple practical utilities, for instance, in better anticipating river-related risks that impact on human safety and property damage, and in improving our ability to design sustainable approaches to river management and restoration. The latter includes promoting catchment management approaches that minimize morphological changes that threaten water resource assets (including river ecological richness), but also measures that *accommodate* the normal range of variability in channel form by allowing 'room for the river' in land-use planning and river restoration (e.g., Cals et al., 1998; Piégay et al., 2005; Florsheim et al., 2008). Understanding the likelihood of morphological change is also critical in forecasting the future 'health' of river ecosystems (Eaton and Millar, 2017), with drivers for change re-cast as 'pressures' or 'stressors' and the morphological response of river channels as 'impacts' or 'stresses' (e.g., NRC, 1992; Piégay et al., 2018). With links now also firmly established between morphological changes and river system functioning in terms of biodiversity losses and ecosystem service values (e.g., MEA, 2005, Gilvear et al., 2013), and the benefits of aesthetically-pleasing landscapes for human well-being (Kondolf and Piégay, 2011; Le Lay et al., 2013), there are multiple justifications for better understanding cumulative impacts on river channel morphology.

Methodologically, understanding the sensitivity of river morphology response to multiple human and natural drivers for change is in its infancy. While researchers have long understood conceptually that adjustments in river channel morphology arise cumulatively from the influence of numerous drivers for change operating at multiple spatial and temporal scales (e.g., Trimble, 1974; Fitzpatrick and Knox, 2000; review in Gregory, 2006), and that they follow an evolutionary trajectory rather than cyclical pattern over historical time periods (Dufour and Piégay, 2009; Brierley and Fryirs, 2016), research studies have generally focused on case studies of the influence of single drivers such as deforestation, urban development, dam building, etc. While single driver studies are valuable for understanding geomorphic processes, they potentially hinder the development of a causally-based, *integrative* science for the fluvial anthroposystem (Piégay, 2016) and implicitly promote a simplistic 'single impact' view of the challenges facing river management and restoration planning. For instance, vegetation encroachment and channel narrowing on the Ain River, France, in the late twentieth century was initially attributed to decreased flows resulting from construction of an upstream dam in 1968 – a quite logical conclusion when considering this impact in isolation and in the context of knowledge regarding the impact of dams (e.g., Petts, 1984; Williams and Wolman, 1984). However, a spatially and temporally more comprehensive study recognized that encroachment and narrowing began in the Ain River and neighboring tributaries before dam construction and is more logically ascribed to earlier forest recovery after abandonment of floodplain cattle grazing (Piégay et al., 2003) following the rural-to-urban diaspora in mid-twentieth century France. Mis-diagnosing the factors influencing fluvial system change is not only poor science that potentially misrepresents the extent of Anthropocene influences on river channel morphology, but it could potentially result in inappropriate or counterproductive management recommendations with significant economic, environmental and legal consequences.

Acknowledging most fluvial systems to be cumulatively impacted by multiple drivers for change, distributed unevenly across a catchment and constantly evolving in time, implies that channel morphological response is a spatially and temporally variable, reach-scale phenomenon. Further, morphological responses can be remote from their spatial cause(s) according to the relative sensitivity of the receiving channel reach, and from their temporal cause(s), with time lags in the order of decades or more. Such variability requires management approaches to vary between locations according to their catchment-scaled, reach-differentiated and time-contingent environmental context (Downs and Gregory, 2004; Brierley and Fryirs, 2016). It also implies several analytical issues that explain the embryonic nature of cumulative impact analyses in fluvial geomorphology. First, cumulative impact analyses require catchment-scale data at relatively high spatial and temporal resolution to determine changes in sufficient and consistent detail (Downs et al*.,* 2013) and, second, the use of secondary historical data imparts an inherent lack of experimental control and the likelihood of greater uncertainties in the historical past.

The aims of this paper are to examine recent approaches to catchment-historical cumulative impact analyses of river channel morphology as the basis for (i) estimating the relative impact of human activities on fluvial systems in the late Anthropocene, (ii) recommending methodological good practice for future studies, and (iii) considering the implications of recent changes for river science and management. Examination is based on a systematic review of recent studies to understand the methods, data and resolution employed, the typically-studied drivers for change, and the characteristic patterns of channel response. Aggregating the results provides a general picture of river channel co-evolution with multiple human activities during the recent historical past.

2. Reach-scale channel responses to catchment-scale multiple drivers for change: a systematic review

A systematic review was undertaken of studies focused on the cumulative impact of drivers for change on channel morphological response. Papers were identified using an electronic literature search (*Web of Science*) to develop a representative profile of research based on multiple search strings that included the term ‘river channel’ with various combinations of ‘change’, ‘evolution’, sensitivity’ ‘catchment’ and ‘historical’. Screening the titles and abstracts of 264 hits produced a list of 90 studies that were reviewed for their ability to satisfy the following eligibility criteria:

1. Involved a *catchment-historical perspective*, rather than only reach-based;

2. integrated the impact of a *comprehensive set of drivers for change* rather than on one or two specific drivers;
3. *differentiated changes at the reach-scale*, rather than indicating only general trends;
4. examined *cause and effect*, rather than simply describing changes.

Some studies meeting these criteria were dismissed following further examination, generally because of insufficient information about the data set used in the analysis or that it was closely related to another paper that shared the same data set. Twenty-five papers satisfied all criteria (Fig. 1). Information related to numerous attributes of the research (Table 1) was extracted manually by the first author and entered into an Excel spreadsheet. The frequent requirement for inference restricted the investigation to a systematic review rather than meta-analysis.

Fig. 1: Global distribution of studies used in the systematic review. Authors: Swale, UK, Foulds et al., 2013; Frome, UK, Grabowski and Gurnell, 2016; lower Rhône, France, Provansal et al., 2014; Drôme, France, Pont et al., 2009; Eygues, France, Liebault, et al., 2002; (middle) Ebro, Spain, Ollero, 2010; Magra, Italy, Rinaldi et al., 2009; Tagliamento, Italy, Ziliani and Surian, 2012; Calore, Italy, Magliulo et al., 2013; Piave, Italy, Comiti et

al., 2011; Fortore, Italy, Scorpio and Rosskopf, 2016; Czarny Dunajec, Poland, Wyzga et al., 2012; Dunajec, Poland, Zawiejska and Wyzga, 2010; Hernad, Hungary, Kiss and Blanka, 2012; Someşu Mic, Romania, Persoui and Radaone, 2011; (lower) Siret, Romania, Salit et al., 2015; (lower) Santa Clara River, CA, USA, Downs et al., 2013; North Fish Creek, WN, USA, Fitzpatrick and Knox, 2000; (middle) Sacramento, CA, USA, Michalkova et al., 2011; Delug, Ecuador, Vanacker et al., 2005; upper Hunter, Australia, Fryirs et al., 2009; Cann, and Thurra, Brooks et al., 2003; Twin Streams, New Zealand, Gregory et al., 2008; Jamuna, Bangladesh, Sarker et al., 2014; Tarim, China, Yu et al., 2016.

Topic	Attributes (units)
Paper	Author names, year, journal
River	Name (Fig. 1), catchment area (km^2) (Table 3), focal time period (years) (Fig. 2)
Study objectives	As stated, or inferred
Resolution (Fig. 3)	
Drivers of change	Total number, scale (classified), names (Fig. 4)
Sub-periods	Total number, years for each period (Table 3), basis for sub-division
Study reaches	Total study length (km), number of reaches identified, position within catchment
Basis for inference	
Data sources	Data types, techniques used (Table 2)
Channel responses	Data type and parameters (Fig. 5), response type (Fig. 8), Intensity and timing of changes (Fig. 9)
Causes and effects	Approach to synthesis, basis of proof, explanation for change
Discussion	Themes in discussion, provision of conceptual model (Figs. 6 and 7)

Table 1: Recorded attributes of research from each study.

3. Results

3.1. Sample characteristics

Not surprisingly given the eligibility criteria, the stated research objectives for sample papers was to determine river channel changes (96% of the sample) and to link the observed changes to their catchment causes (92%). Thirty-two percent of papers also included a specific objective related to river management and 16% stated a desire to derive conceptual advances. Only three (12%) were concerned with predicting future evolution highlighting that the study sample was overwhelming focused on retrospective analysis. No studies before the year 2000 met all eligibility criteria: this is ascribed to the highly laborious manual data collection and processing required prior to the advent of Geographical Information Systems (GIS) for manipulating and integrating extensive and diverse data sets over catchment to long-reach scales (see Downs, 1994, 1995). Recent research on the topic has also been greatly facilitated by readily-available digital elevation models and thematic digital data sets (e.g., for land cover, etc.) – moves toward open-source data may further improve opportunities for holistic perspectives on this topic.

The global distribution of the study sample is illustrated in Fig. 1. The concentration towards European catchments is speculated to reflect some combination of the influence of certain scholars, prevailing national philosophies towards ‘physical geography’, historic national investment in high quality cartography, and countries in which river channel change is of sufficient societal concern to encourage research linking channel changes and human actions. This latter factor may include inputs to public policy and legislation such as those driven by the EU Water Framework Directive.

3.2. Techniques used, and data employed

Methodologically, the sample papers represent studies in ‘historical fluvial geomorphology’, reviews of which have punctuated the last 40 yr (e.g., Hooke and Kain, 1982; Trimble and Cooke, 1991; Trimble, 1998, 2001, 2008; Gurnell et al., 2003; Gregory and Downs, 2008; Grabowski and Gurnell, 2016). Many reviews have included summary tables of the main techniques and sources of evidence: the derivative provided in Table 2 thus represents the approaches used, *in practice*, for catchment-scaled, historical fluvial system research in the early twenty-first century. In spatial terms, traditional sources and techniques of land surface mapping using topographical and thematic maps are now supplemented by a range of remotely-sensed imagery, instrumented surveys incorporate digitally-derived channel and floodplain topography in addition to cross-sectional surveys, and river channel mapping may utilize data from spatially extensive reconnaissance surveys (e.g., River Habitat Survey) in addition to field and bed sediment mapping. Spatial analyses may also integrate numerical modelling techniques such as flow simulations and various forms of terrain analysis are commonplace, including detection of channel changes using image differencing within GIS. Temporal data derived from instrumented time series and floodplain sedimentology is being complemented by an ever-broadening range of thematic historical records to represent drivers for change and by the increasing variety of techniques available for dating sedimentary deposits. Overall, Table 2 indicates the extensive array of data required for undertaking such catchment-scale cumulative impact studies and perhaps explains why studies were difficult to achieve before fully-functional GIS.

Category of technique	Data Sources
Spatial information	
Land surface mapping	Topographical, historical, geological, land cover
Remotely sensed imagery	Aerial, ground, LiDAR, satellite
Instrumented surveys	River channel cross-sections, bed elevation surveys, bathymetry, floodplain topography
River channel mapping	Field, bed sediment, habitat surveys (e.g., RHS)
Numerical modelling	Hydraulic modelling, rainfall-runoff modelling
Planform and terrain analyses	Planform overlay, DEM generation and differencing
Temporal information	
Instrumented time series records	Flow/sediment gauging, water levels, flood records, precipitation records
Historical records / contemporary records	Infrastructure construction dates, river engineering records, mining records, wildfire archives, survey notes, archives, agricultural surveys, population growth, forest cover rate
Floodplain / paleochannel sedimentology	Floodplain/paleochannel sections, facies interpretation, sediment cores
Relative and absolute dating techniques	Geochemical, isotope analysis, radiocarbon dating, dendrochronology, lichenography, artefacts

Table 2: Techniques used in analysis and data sources employed.

3.3. Scale and resolution of studies

The sample papers represent catchments over four orders of magnitude, but with the majority (25^{th} – 75^{th} percentile) ranging from 600 to 6000 km^2. Median catchment size is approximately 3000 km^2 (Table 3). Minimum catchment size is probably constrained by needing a sufficient variety of drivers for change to warrant research while, conversely, the volume of information required for very large catchments is both daunting and makes summary statements difficult to achieve. Median study length was 84 km, but this was highly variable (range 5.5 – 900 km) (Table 3).

A fundamental constraint on study inclusion was the need for *reach-differentiated* records of channel response. Studies are thus constrained temporally to a period between the availability of the first accurately surveyed maps (generally <200 yr) and a final date based on the last available set of maps or images before the study's conclusion (Fig. 2). Study dates were thus in the range 1851 to 2009 (25th percentile start date – 75th percentile end date) with study timeframes of 72 to 151 yr (median 127 yr, Table 3). The primary outlier in Fig. 2 involves a 'Holocene-scaled' study (Foulds et al., 2013) that, somewhat uniquely, derived reach-scale response changes over a catchment extent – other screened studies encompassing Holocene time periods restricted reporting of changes either to catchment generalizations, point data, or to detailed descriptions for single reaches and as such failed to fulfil the 'reach-differentiated' criterion.

	Area (km^2)	**Study length (km)**	**Start Year**	**End Year**	**Timespan**
Minimum	61	5.5	1100	1950	31
25th percentile	602	35.5	1851	2000	72
Median	**2950**	**83.5**	**1878**	**2005**	**127**
75th percentile	5781	140	1932	2009	151
Maximum	1,020,000	900	1963	2015	850

Table 3: Ranges in temporal and spatial extends for the sample study set.

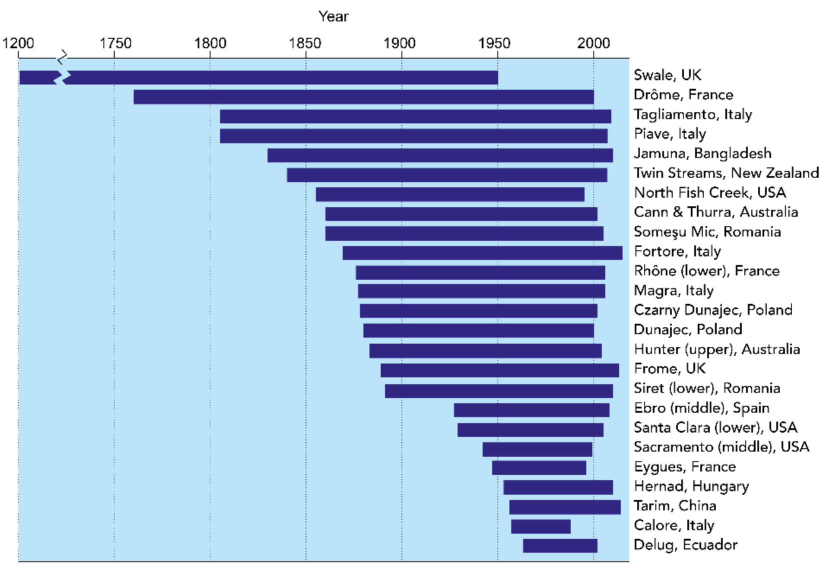

Fig. 2: Stated time periods for the sampled studies.

Studies were chosen according to their stated intention of undertaking an assessment of cumulative impacts. The overall resolution of each study therefore involved a variable number of drivers for change generalized over different sub-periods of time and over different numbers of reaches (Fig. 3). On average, studies involved 5.5 drivers for change spread across 4 different spatial scales (see below) and were sub-divided temporally into 3 sub-periods (range 1-5) and 12 study reaches. Interpretation of time periods was occasionally complicated by discussion of a period pre-dating the stated starting date. Temporal sub-periods were split according to distinct phases in human activity or distinct types of channel response and were not necessarily synchronous across the catchment. Whereas most authors provided a summary statement of their sub-periods, inference was occasionally necessary. While study results were split over an average of 12 reaches, variability was high (standard deviation of 12 reaches) reflecting whether sub-division was based on a general rule set, divisions at incoming tributaries, a series of (usually short) equal-length segments, or as non-contiguous focal reaches. In studies using the River Styles approach (Brierley and Fryirs, 2000, 2005), the number of reaches was defined by the number of River Styles identified as the number of reaches was not enumerated.

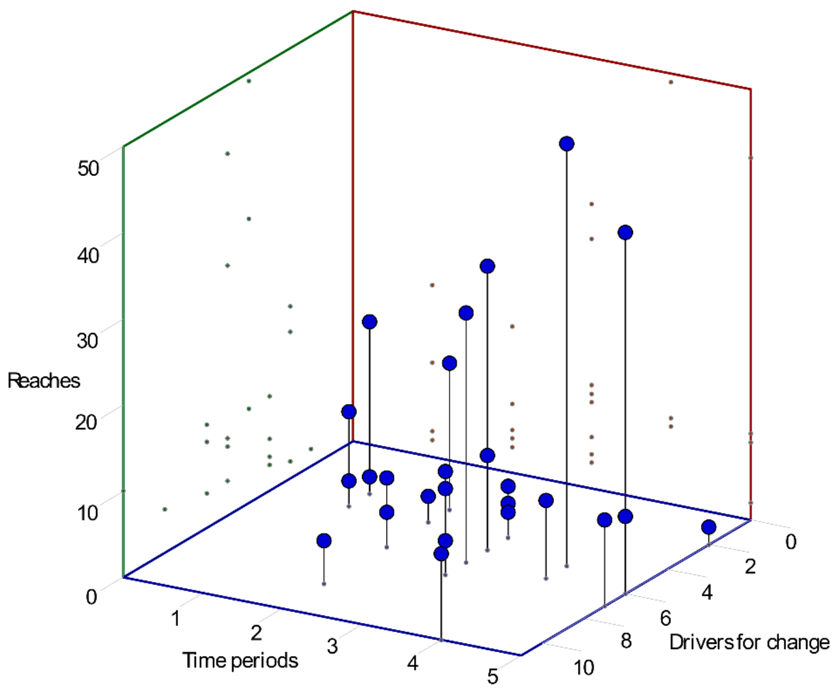

Fig. 3: Sample study resolution as a function of the stated drivers for change, defined number of channel reaches within the study extent, and defined sub-periods within the study timeframe.

3.4. Typical drivers for change and metrics of channel response

Each study was unique according to the particular suite of natural factors and human activities that drove changes in that catchment, and to the various morphological metrics used to describe channel response, such as width, depth, sinuosity, channel pattern, etc. Drivers for change were classified into seven notionally-discrete spatial scales (Fig. 4). Overwhelmingly 'natural' drivers included atmospheric factors representing the catchment's hydroclimate or flow regime, and contextual river basin factors such as lithology or structure and whether tectonic activity was an influence. Such factors thus indicate whether catchments are intrinsically more or less responsive to change or determine key disturbance events, cycles or trends in natural forcing. Human influences also included catchment-scale factors, such as 'land cover' alterations but, in addition, incorporated network, riparian, reach and 'local' scale impacts that frequently reflect priorities for water resources management (e.g., damming) or engineering works intended for flood control or channel stability. Unsurprisingly, most studies (76%) were placed in their hydroclimatic context, establishing flow regimes based on gauging station data or rainfall, or using data relating to flood frequency: there was an equal likelihood of using either data type (44%, 11 of 25 studies, Fig. 4), but only three studies used both. The case study and 'human impact' focus of this research is perhaps emphasized in that 24% of studies did not provide any hydroclimatic or basin scale natural factor contextualization, despite the influence of these drivers on sediment loading and potential sensitivity to change of the responding river channels. Only one study reported more than one basin factor.

Of the human drivers for change, 'land cover' alterations can, of course, be multifaceted over a catchment extent, and 36% of papers indicated more than one cover change. Further, the exact alteration(s) implied by studies was not always explicit, necessitating provision of a generic 'land-cover change' driver. This generic driver, along with deforestation or afforestation was implicated in 44% of studies, with 80% of studies mentioning one or the other. Twenty percent of studies explicitly indicated agricultural change (although such changes were probably implied in many of the 'land-cover change' entries) or urban growth (sometimes by statistics representing population growth). At the network scale, 72% of studies included an entry related to changes in flow and sediment supply at the network scale - predominantly this related to the construction of one or more large dams (48% of studies) that, of course, may have been implicated in the flood frequency driver. The second most frequent concern at this scale was for 'tributary regulation' (28%), which here implies modifying flow or sediment supply to the mainstem river usually by channelization or check dams, thus reflecting several studies located in the Alpine fringes of Europe. Seventy-six percent of studies indicated reach-scale management actions with many studies indicating more than one activity, the most popular combinations being bank protection (52% of studies) and instream aggregate mining (48%). Other forms of channelization were indicated in 28% of studies. In contrast, fewer drivers for change were indicated at the riparian or local scales, although channel embankments for flood control were reasonably common (28% of studies).

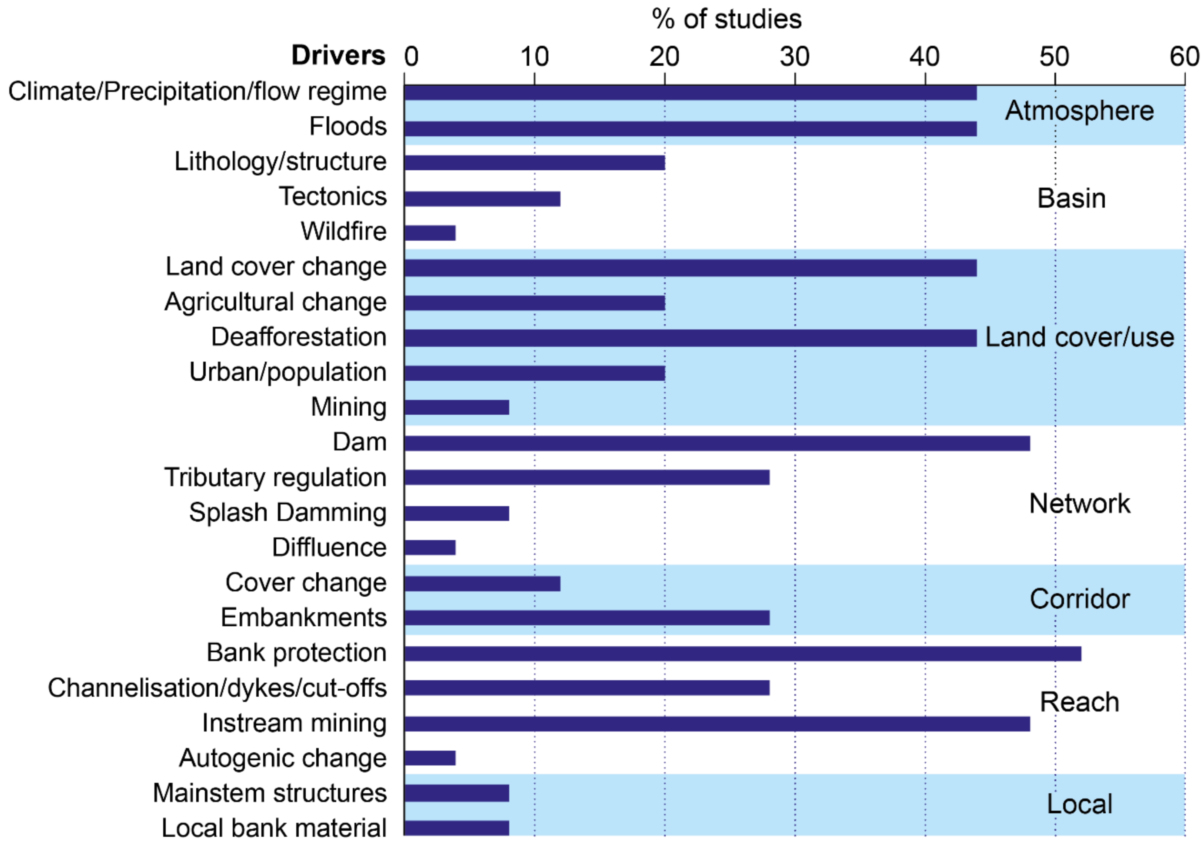

Fig. 4: Named drivers for change arranged by scale.

Response of channel morphology to the studied drivers for change encompassed a wide variety of metrics (Fig. 5) representing a far broader conception of change than the 'degrees of freedom' involved in analytical studies. Response metrics usually referred to reach-scale changes on the mainstem channel in the middle or lower parts of a catchment – far fewer studies described tributary changes. Responses in Fig. 5 are categorized according to whether they represent changes in channel form (e.g., width), sedimentary characteristics of the river bed or banks, floodplain stratigraphy or erosion and riparian vegetation, meander attributes, channel pattern, or process factors such as shear stress or form roughness. Studies overwhelmingly included an indication of change in the active channel width (80% of studies) – frequently, but not exclusively indicating changes in bankfull width. Forty-four percent of studies indicated changes in bed elevation or channel depth and over 20% of studies each indicated changes in sinuosity, channel typology, or an index of braiding. Linked to sinuosity, channel (centerline) length was also named in five studies emphasizing that the named drivers are not mutually exclusive. The focus on channel width, meanders and channel pattern attributes is assumed to reflect the relative ease with which 'horizontal' metrics can be extracted from a mapping system, as opposed to vertical features such as channel depth that require a historical commitment to channel survey or field interpretation.

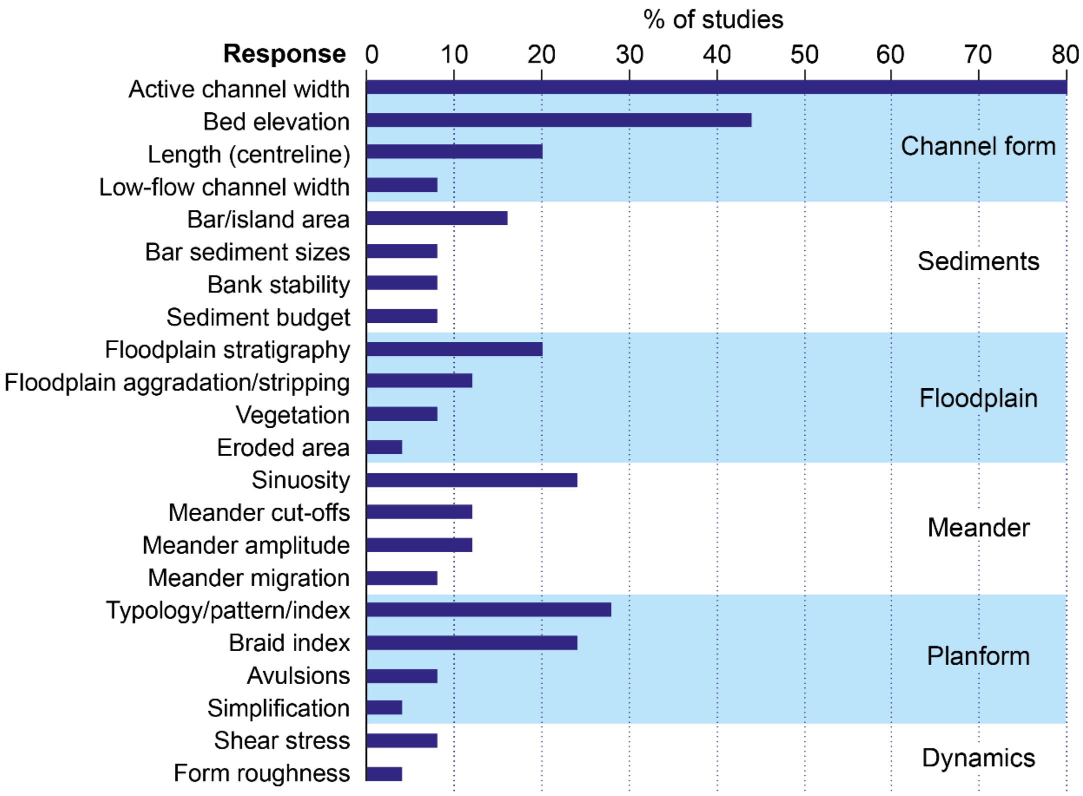

Fig. 5: Stated response metrics, categorized by type.

3.5. Methods for associating cause and effect

The most limiting criterion for papers to be accepted into this dataset was a professed interested in *explaining* river channel changes through a system for ascribing cause and effect, rather than just *describing* changes. Various methods are conceivable, including analytical modelling, statistical tests or volumetric correspondence and, while such approaches were used occasionally (Liébault et al., 2002; Rinaldi et al., 2009; Comiti et al., 2011; Ziliani and Surian, 2012; Salit et al., 2015; Grabowski and Gurnell, 2016), in nearly all cases the primary basis for ascribing cause and effect was expert interpretation by the authors. Further, 'proof' was based overwhelmingly on the temporal synchronicity and spatial proximity of channel responses with the deemed causal factors. There was no case in which a fully analytical approach was undertaken that negated the need for expert interpretation. Neither were there any examples where an analytical approach was used to examine potential time lags between cumulative impacts and subsequent channel response. This despite evidence in the fluvial system literature for decadal or greater lags in channel response to individual drivers of change (since Graf, 1977), and studies that have detected time lags by propagating (sediment-related) changes through time (Liébault et al., 2005; Rollet et al., 2013).

The primary vehicle for conveying a summary of the study findings was one or more summary evaluations presented as a conceptual model (44% of studies). Generally, such models are temporally focused on the synchroneity of channel responses with a series of possible causal drivers for change in a style reminiscent of the timeline evaluation in a 'fluvial audit' (Sear et al., 1995; examples in Fig. 6). The notable difference here was that the channel responses are often quantified, and so too the drivers for change, and there is frequently a measure or judgment of the 'intensity' of association between responses and the inferred drivers of change (e.g., Hoyle et al., 2008; Pont et al., 2009; Ziliani and Surian, 2012; Downs et al., 2013; Sarker et al., 2014). The primary exception to the 'fluvial audit' style of figure arises where a time-sequence trajectory of cross-sectional changes are provided (e.g., Gregory et al., 2008; Pont et al., 2009, Fig. 7), generally as an output of the River Styles approach (Brierley and Fryirs, 2000). In either situation, temporal bounding of periods assumed to significantly associate drivers of change and channel responses is often paramount and confirms the focus of many studies in developing a retrospective history of changes, rather than using conceptual models for pursuing a hypothetico-deductive perspective on channel change (e.g., Liébault and Piégay, 2002).

Few studies conveyed reach-scale differences very effectively, perhaps because simultaneously representing drivers for change, temporal changes and reach-scale change s implies a three-dimensionality not easily depicted in a two-dimensional figure. However, efforts to indicate the functional representation of changes included a cascading propagation of changes from causal factors to channel responses (Pont et al., 2009), a spatial perspective on responses (e.g., from upstream to downstream: Pont et al., 2009; Scorpio and Rosskopf, 2016) or a multiscale perspective (Downs et al., 2013).

4. Integration: river channel evolution in the late Anthropocene

4.1. Aggregated channel response

The channel responses depicted in Fig. 8 indicate how multiple natural factors and human activities have influenced the global (industrial nation-focused) evolution of river channel morphology in the recent Anthropocene, since about 1880, according to the sample of 25 'comprehensive' cumulative impact studies. The examples represent 287 river reaches in total although response trends were often described in aggregate terms rather than by reach. Instances of 'inferred change' were minimized by restricting responses to those clearly stated by the authors. Not all studies reported on all their stated response metrics (Fig. 5) and some studies reported responses beyond those originally stated as metrics, for instance in reporting vertical changes such as bed incision as an apparent result of inferences made during field studies. Types of response are indicated by frequency in Fig. 8, with responses categorized according to implied process changes, including apparent increases or reductions in flow discharge or sediment load, increases or decreases in rates of channel activity, or changes in meander geometry or bed sediment. Channel responses commonly fluctuated between reaches and in time, thus many studies illustrated, for example, contrasting spatial activity between reaches that narrowed and those that widened, and contrasting time periods in which the same reach may have widened and then narrowed, etc.

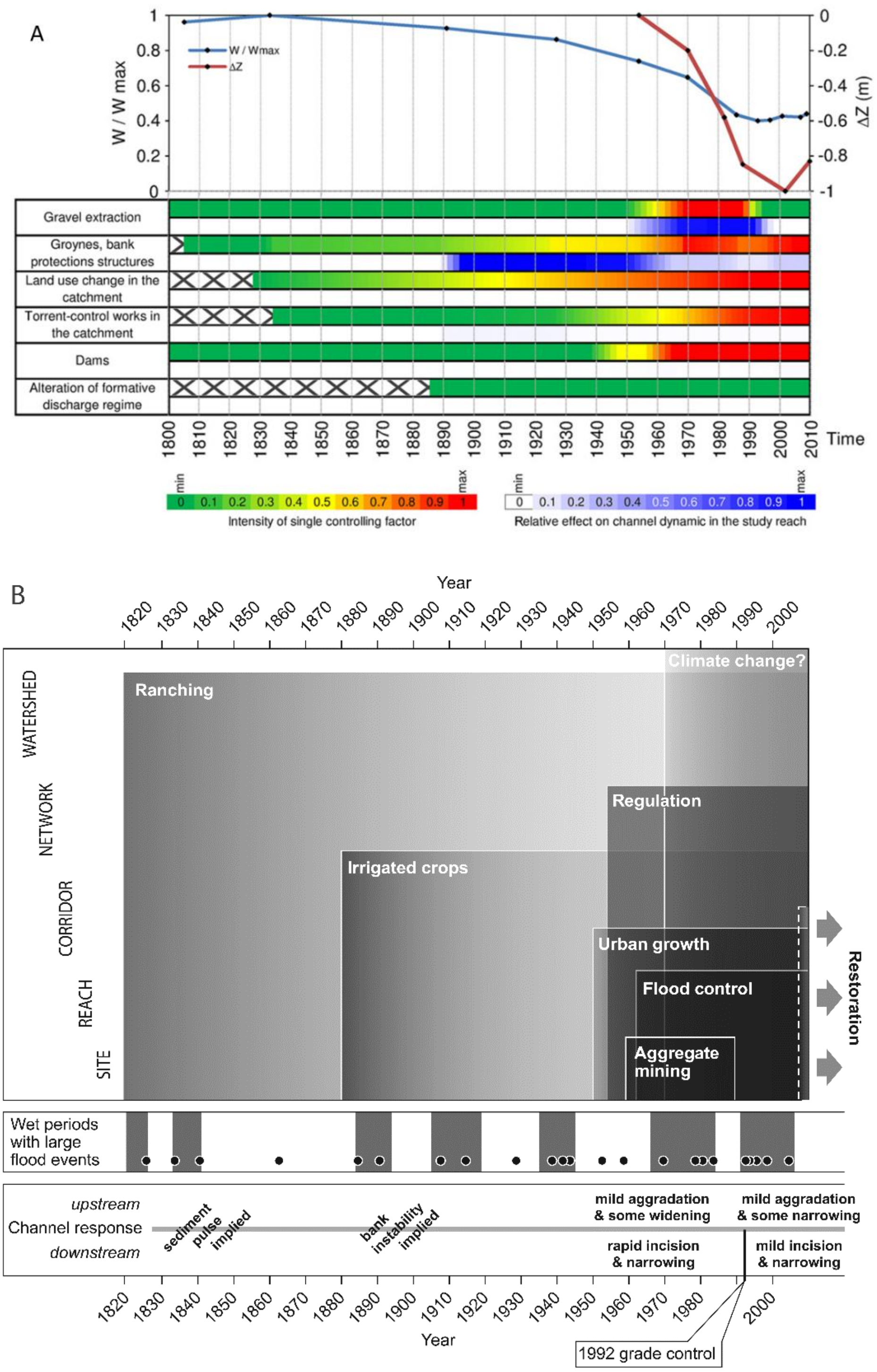

Fig. 6: Examples of cause and effect summaries depicted as conceptual models focused on temporal synchronicity of changes with relative intensity with single drivers for change: (A) Ziliani and Surian (2012, their Fig. 12), depicting changes in channel width and depth against color-coded intensity of drivers (reproduced with permission from Elsevier); (B) Downs et al. (2013; their Fig. 8) where relative intensity drivers for change are overlaid at their corresponding spatial scale to indicate when and at what scale impacts appear to be maximized, and differences between upstream and downstream channel response (reproduced with permission from Elsevier).

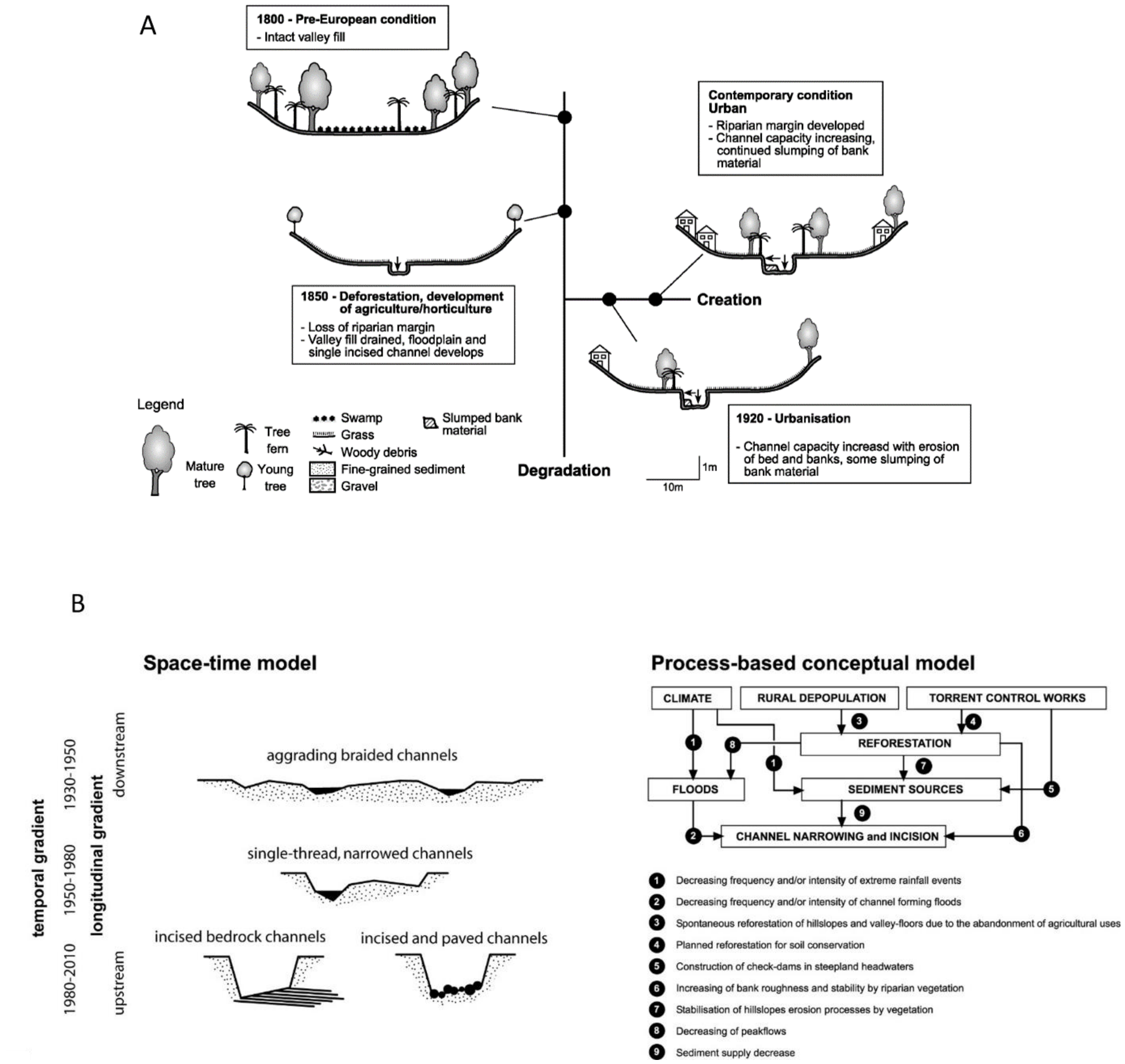

Fig. 7: Examples of cause and effect summaries depicted as conceptual models focused on interpreted evolutionary trajectories. (A) Gregory et al. (2008, their Fig. 5B) describing changes along a degradation trajectory and the creation of novel ecosystems arrangements (reproduced with permission from Taylor & Francis); (B) Pont et al. (2009, their Fig. 4) depicting both a space-time trajectory of change and the assumed process changes that explain the observed changes (reproduced with permission from Springer Nature).

Overall, in the 125-yr period to 2005, the predominant response to multiple drivers for change in the study sample is for channels to have become narrower, incised, to have developed terraces and reduced bed sediment storage, rather than to have widened, aggraded their bed or floodplains and increased bed sediment storage (Fig. 8). Further, they have become less rather than more active, with reduced rates of lateral activity, simplified channel geometries, a greater proportion of 'static' channels, with braided reaches converted to single thread and actively meandering channels to sinuous. Counteracting such simplification is arguably the fundamental basis for river restoration (Peipoch et al., 2015). From Fig. 4, evolutionary changes can be implied to result in general from the combined influence of flow or flood regime changes, the construction of dams and bank protection, changes in land uses and forest cover, and as a response to instream sediment mining operations: with most of these changes inferred to imply reductions in sediment supply.

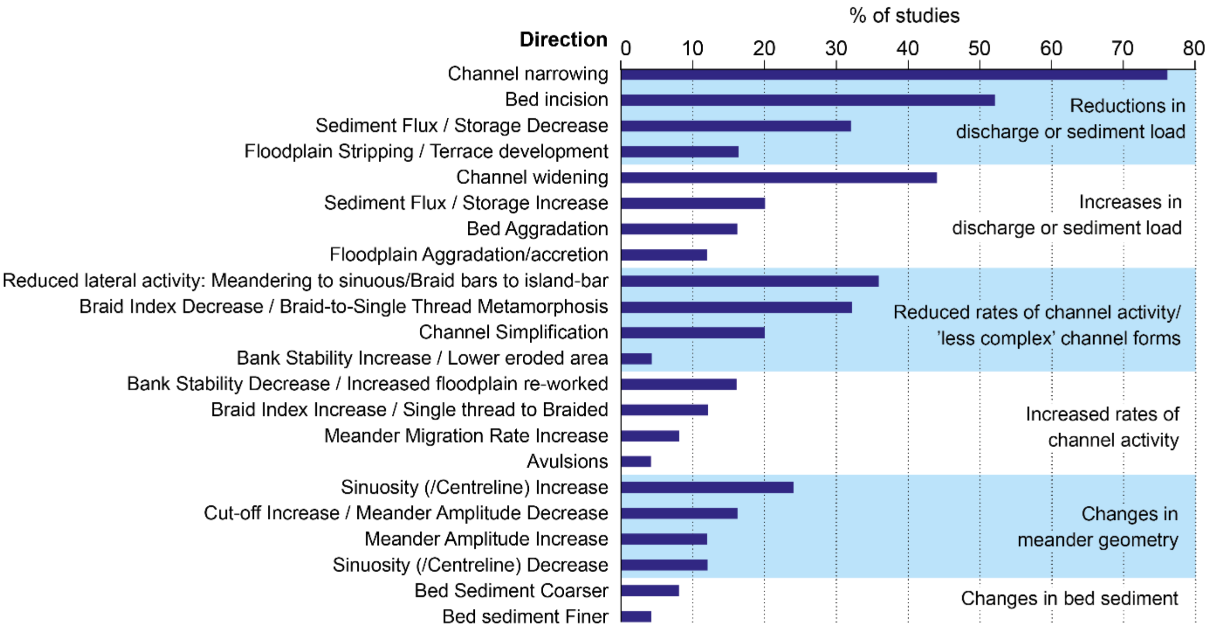

Fig. 8. Evolutionary trajectory of river channels in the late Anthropocene. Response metrics are coded according to their interpreted implication for channel processes.

4.2. Intensity and timing of change

Most studies included a summary assessment of changes through time (directly stated or inferred) indicating periods of general stability versus periods of most intense channel change and fluctuating channel changes in time. Fig. 9, which clusters studies by region, highlights those periods described by authors as having the most intense or distinct channel changes and those of the greatest period of inactivity. As with many studies using historical data, the accuracy of statements or inferences may be biased by greater data availability in more recent decades that allow a more nuanced understanding of change.

Fig. 9 depicts a variety of different channel responses happening before 1955, *conceivably* hinting at the influence of differentiated human activities rather than overriding atmospheric controls as the primary factor in determining channel response. Several examples where intense channel change occurs towards the beginning of the study period are those areas subject to rapid European colonization (e.g., in Australia and New Zealand: Gregory et al., 2008; Fryirs et al., 2009) or rapid land use change (e.g., in France with rapid deforestation in tributaries of the River Rhône such as the Drôme, Pont et al., 2009) followed by extensive channelization works on the mainstem that curtailed further (lateral) channel response (Provansal et al., 2014). Such associations are not, of course, irrefutable evidence for the predominance of human influence.

Notably, the proportion of channels undergoing their most intense period of described change increases after 1955 from around 20% to around 50% and then again to 65-75% during the period 1970-1990. Rates of most intense change progressively decrease to approximately 40% by 2005, after which the sample size is too small for meaningful interpretation. In contrast, studies reporting greatest channel stability progressively increase after 1985 (to five channels in the period from 1995). Overall, from 1970 to 2005, 70% or more of studies report their most distinct period of either channel change or inactivity. Included in Fig. 9 is a summary statement of the inferred change, with evidence strongly suggesting that these intense changes relate to channel narrowing and incision in the period starting from 1950-1970, decreasing again in the period from 1990-2000.

Overall, there is period of 20 to 50 yr from the mid-twentieth century in which channels changed intensely, whereas channel stability became increasingly commonplace in the last decade or two of the twentieth century. While possibly related to climatic signals, such changes are also synchronous with the proposed 'Great Acceleration' phase of the recent Anthropocene (Steffan et al., 2007; Zalasiewicz et al., 2010). Channel incision may be a response to extensive channelization and instream mining following the end of the Second World War, and/or responses that followed the 'golden age' of dam building (1960-1980, Beaumont, 1978). Increasing stability later in the century may indicate the completion of these channel responses or to the influence of bank protection in increasing resistance to change. Conceivably, reduced rates of activity might also result from the impacts of environmental impact legislation regulating channel and riparian engineering (in the US since 1969 and the EU since 1988), or to the uptake of sustainable approaches to river management (e.g., river restoration) since about 1990 (Bernhardt et al., 2005).

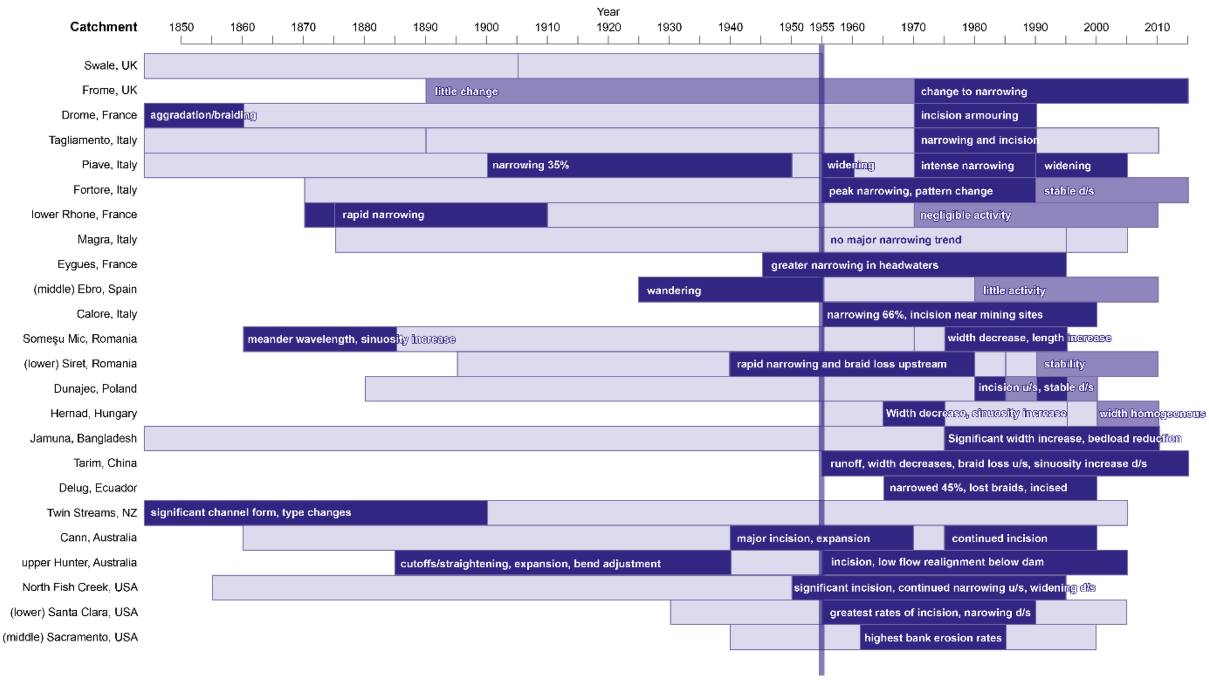

Fig. 9: Stated or inferred intensity of morphological changes from the sample studies, organized by region. Light shade defines the study extent, mid-shade the period of greatest channel stability, and dark shade the period with the greatest rate of change. Brief descriptions are provided for the latter categories. The period of greatest changes frequently occurs after 1955 (emphasized).

5. Discussion

5.1. River evolution and evidence for the late Anthropocene in fluvial geomorphology

A systematic review of literature on the cumulative impacts of natural and human drivers for river channel change, focused on medium-sized river catchments (~600–6000 km^2, and with some bias towards industrialized, European catchments (Fig. 1), provides evidence for the co-evolution of river channels with multiple human activities over a period of approximately 125 yr (1880-2005, Fig. 2). Using a variety of analytical methods (Table 2), the 25 qualifying studies examined cause and effect associations implicit to reach-differentiated channel response to multiple drivers for change at the catchment scale. The studies generally focused on extensive lengths (27-140 km) of mainstem or lower mainstem channels, splitting them into numerous reaches and to 2-4 time periods of differentiated responses (Fig. 3). Studies typically assessed river responses to 5-6 drivers for change, with the most commonly associated drivers including catchment-scale factors such as changing flood and flow regimes, dam construction, and changing land uses and forest cover (in particular), and more local-scale factors such as bank protection and instream aggregate mining (Fig. 4).

In response to these causes, that act predominantly to reduce sediment supply, river channels have typically narrowed, incised into their bed, reduced their lateral activity rates, changed from multi-thread to single-thread channel patterns and reduced their storage of bed sediments (Fig. 8) during the late twentieth century, with potentially significant deleterious effects on aquatic and riparian biodiversity (see below) and resilience to human pressures. Such changes, if replicated more widely, may give credence for a river morphology-focused 'Great Acceleration' phase of the Anthropocene since ca. 1950, with river morphologies becoming initially more sensitive to drivers for change, peaking in the 1970-1990 period, before lower activity rates become more commonplace from about 1990 (Fig. 9). Given the commonly associated drivers for change, a stereotypical model of post-World War Two human causes involved changes in forest cover, agricultural intensification, significant increases in technological capacities and population growth that promoted the 'golden age' of dam building, increases in instream mining to provide building aggregates, and the consequent need for bank protection (or channelization) to protect floodplain developments from river migration and incision processes. Essentially, river systems were over-exploited during late-twentieth century economic growth, if not before. An approximation to this generic model exists in many of the studied catchments (e.g., Fryirs et al., 2009; Pont et al., 2009; Rinaldi et al., 2009; Ollero, 2010; Comiti et al., 2011; Michalková et al., 2011; Persoiu and Radaone, 2011; Downs et al., 2013; Scorpio and Rosskopf, 2016), with dam building and aggregate extraction frequently considered to be the dominant causes.

Variants on this general trend in the study sample result from the specific responsiveness of individual river basins to factors such as the influence of large flood events (Comiti et al., 2011; Kiss and Blanca, 2012; Salit et al., 2015), the role of bedrock exposure (Zawiejska and Wyzga, 2010), extensive urbanization (Gregory et al., 2008) and due to the cessation of instream mining (Ziliani and Surian, 2012). Elsewhere, a different picture emerges entirely (e.g., Fitzpatrick and Knox, 2000; Liébault et al., 2002; Brooks et al., 2003; Sarker et al., 2014; Grabowski and Gurnell, 2016; Yu et al., 2016), emphasizing the role of different regional and catchment histories and within-catchment locational factors (i.e., headwater stream versus mainstem channels) in producing results that are unique but not singular (Schumm, 1991).

Reductions in rates of channel morphology change since ca. 1990 are conceivably indicative of a nascent 'fourth phase' of the Anthropocene (Crutzen and Steffan, 2003) characterized by responsible stewardship of the Earth system (e.g., the temporally coincident growth in practices of sustainable river management and restoration, Bernhardt et al., 2005, their Fig. S1). However, it may also reflect channels 'forced' into insensitivity through a combination of flow regulation resulting in flood suppression, channelization and bank protection measures (e.g., Ollero, 2010; Downs et al., 2013; Scorpio and Rosskopf, 2016. The latter interpretation argues for a continuation of the Great Acceleration wherein suppression of Earth processes is achieved through highly restrictive management practices that reinforce the dominance of humans over nature, including through 'technocratic' river restoration practices (Eden and Tunstall, 2006).

The preceding analysis provides reasonably consistent evidence that river evolution over the last 125 yr (and particularly since about 1950) has resulted in morphological configurations that have no prior analogue (Gaffney and Steffan, 2017), Instead, river channels have co-evolved directly in response to the sedimentary process cascade alterations resulting from human activities to result in morphologically-novel outcomes. Whether such changes represent proof for the proposed Anthropocene epoch depends on whether evidence is required for the 'overwhelming' impact of human activities on the Earth system (Steffen et al., 2007) or simply the 'significant' capacity for ecosystem engineering (Smith and Zerder, 2013). For the latter, late-twentieth century river evolution may simply illustrate the *continuing* existence of the Anthropocene, with the period having begun with river modifications related to the onset of organized agriculture in the Near East in the Early Holocene with a subsequent spread and intensification worldwide (Gibling, 2018).

Evidence for an *overwhelming* impact is more challenging of cause and effect relations, with results that are potentially disciplinarily-specific and divergent (but see Steffan et al., 2015). In this regard, the reviewed studies are far less convincing about *which* drivers for change are ultimately responsible, and the relative influence of human factors versus changes in flooding and bedload regimes caused by natural climatic oscillations and periodicities. Ascribing cause and effect is certainly challenging: channel changes resulting from natural forcing (e.g., resulting from the Little Ice Age) are potentially disguised in highly populated landscapes because they are 'filtered' by human activities to produce gradients of change rather than cyclic patterns. Conversely, channel responses to human activities frequently require the stimulus provided by flood events making the time frame for adjustment highly variable according to flood regime intensity (e.g., downstream of dams, Petts, 1979). Such interdependencies apart, statements regarding cause and effect in the reviewed studies were drawn almost exclusively from expert interpretation rather than mathematical or statistical 'proof', rather than using paired, comparative or otherwise synchronic studies (see Brooks et al., 2003, Collins et al., 2012, Piégay, 2016), and the studies focused heavily on the various human activities rather than controlling for climate-driven fluctuations in flow and sediment regimes that might trigger such changes. An authoritative conclusion on the impacts of the Anthropocene in fluvial geomorphology (cf. Brown et al., 2017) thus awaits analytical advances (including better data collection, archiving and sharing) that allow greater rigor in cause-effect determination under situations of cumulative impact.

5.2. Cumulative impact analysis in fluvial geomorphology – moving beyond the case study

Drawn from recent peer-reviewed literature, the studies reviewed here should represent best-practice approaches for cumulative impact analysis in fluvial geomorphology, retrospectively linking multiple prospective drivers for change distributed across the catchment with reach-scale responses of the channel morphology. The studies post-date many decades of empirical research regarding the impact of various individual drivers for change, and the subsequent development of advanced conceptual ideas related to channel response. This includes notions of hierarchical scales of influence, spatially- and temporally-remote causes and effects, system feedbacks, exponential decay rates, step functions of impact diffusion (synthesis in Brierley and Fryirs, 2005) complex historical and geographical contingencies (Phillips, 2006) and reach-differentiated *sensitivity* of river channel responses to drivers for change in terms of their likelihood, location, persistence and relative magnitude (Downs and Gregory, 1995, 2004; Fryirs, 2017). Notably, the reviewed studies almost all use expert judgment to interpret the resulting patterns of channel change based on temporal synchronicity and spatial proximity of causal features. Thus, they are essentially practicing *abductive reasoning*, using the existence of a pattern of outcomes as the basis for inferring the most likely causes. While, geomorphic science has a proud tradition of using abductive reasoning as the basis for hypothesis formulation (Baker and Twidale, 1991, p. 89-90), the studies here frequently conflate abduction and induction to result in somewhat circular reasoning of cause and effect, rather than abducing the most likely hypotheses as the basis for a controlled (deductive) examination of change propagation, as achieved for single-driver studies (e.g., Liébault, 2003; Liébault et al., 2005; Rollet et al., 2013). Exceptions occurred primarily in studies analyzing multiple channels, including the use of multivariate statistical discrimination to associate cause and effect across multiple headwater streams in the French Prealps (Liébault et al., 2002) and the interpretative comparisons enabled by a paired study in southeastern Australia (Brooks et al., 2003), and a highly preliminary attempt to quantify sensitivity in Downs et al. (2013, their Table 5).

Overwhelmingly, though, the reviewed studies are exploratory empiricisms on the topic of cumulative impact, seeking to discover patterns of change – a 'meaningful clustering of experiences' (Kwasnik, 1999, p. 24) in a single mainstem channel. Such approaches are commonplace in the initial stages of scientific research on a new topic (e.g., Kondolf and Piégay, 2016), and reflect the methodological infancy of cumulative impact studies. They are also perhaps amplified in geomorphology due to its tradition of structured observation of uncontrolled data sets (Rhoads and Thorn, 1996), accentuating the importance of pattern discovery prior to structured hypothesis testing (Wilkins and Ebach, 2014; Kondolf et al., 2016). Pattern discoveries were frequently expressed by summary evaluations that conceptualized the outcomes (examples in Figs. 6 and 7), perhaps mirroring Gregory and Lewin's (2015) observation that recent geomorphology research has focused on empirical discoveries driven by technological advances – here, the availability of GIS, catchment-scale digital data, new surveying methods and analytical models – rather than on explicit discussion or test of concepts of cumulative impact (e.g., Liébault and Piégay, 2002). It is perhaps unsurprising that cumulative impact studies prescribe a mixed inductive-abductive approach as authors grapple with the breadth of the catchment data sets and the essential novelty of an *antireductionist* (i.e., holistic) approach to study facilitated by the new technologies. The aims of this paper intrinsically form part of the knowledge discovery process: "…each research community at various points must gather up the disparate pieces and in some way communicate what is known, expressing it in such a way to be useful for further discovery and understanding" (Kwasnik, 1999, p. 23).

Presently, geomorphologists are apparently far better at observing and stating changes than ascribing cause and effect for cumulative impacts, which was here dominated by spatial and temporal proximity. Among other issues, this will likely bias attribution of causal influence towards local factors rather than spatially-extensive drivers such as land-use changes. Whether such bias is warranted remains to be proven, but it is critical for conceptual understanding to be translated into practical approaches for holistic analyses both scientifically and because of geomorphology's increasingly prominent role in river and catchment management. Table 4 summarizes attributes of recent research and provides recommendations for a more structured and deductive approach to understanding cumulative impacts in river channel evolution. Analogies to the best-practice attributes of environmental model building (Jakeman et al., 2006, their Fig. 1), suggest that the process should be subject to similar steps, including the need for internal calibration. Studies should use a combined diachronous-synchronous approach (Piégay, 2016), integrating data from catchment- to reach-scale studies over several time periods (dictated by data availability, e.g., the timing of aerial photography). And, whereas previous studies have been based primarily on expert judgment, future approaches should include explicit functional assumptions, including (but not restricted to) those drawn from single-driver studies of change and combined field-numerical-experiment approaches, be adequately framed, conceptually (*sensu* Gregory and Lewin, 2018), and be capable of accommodating 'confounding' spatial and temporal factors such as discontinuity, diffusion and time lags. The results should be precise, with an accuracy governed by the assumptions inherent to model construction, and lead to predictions of future performance and sensitivity analysis of 'what-if' scenarios. The use of secondary historical data may restrict opportunities for undertaking structured error analysis (similar concerns exist in sediment budget analysis: Hinderer et al., 2012; Reid and Dunne, 2016; but see Downs et al., 2018), putting further emphasis on independent validation of the analyses. Studies should clearly state the facts that support cause-effect conclusions and provide suggestions for further research.

Approaches to cumulative impact model building could be based on distributed process mechanical erosion models (e.g., WEPP – Flanagan et al., 1995, 2007, 2012), 'reduced complexity' finite-element terrain models (e.g., CAESAR – Coulthard et al., 1999, an initial approach for single drivers of change in Ziliani and Surian, 2012), or network-scale sediment connectivity models (e.g., CASCADE - Schmitt et al., 2016). Statistical-based approaches could be employed that explore the inherent hierarchical clustering to drivers of change or that accommodate nominal data probabilistically (e.g., using logistic regression - early experiments by Downs, 1994, 1995). A recent prospect, increasingly used in the environmental sciences neighboring geomorphology, uses Bayesian probabilities within a Belief Network framework (e.g., Castelletti and Soncini-Sesa, 2007; Allan et al., 2012; Forio et al., 2015; Van Looy et al., 2015; Van Looy and Piffady, 2017). Bayesian approaches are well-suited for deriving explicit and complex cause-and-effect relationships using probabilistic relationships when, as here, the mechanistic structure of the relationships is not clear (Borsuk et al., 2004). Further, the expert rule-based system of conditional probabilities provides a transparent (i.e., white box) structuring of model assumptions that is amenable to progressive improvement as knowledge advances.

Attribute	Studies to date	Proposed future studies
Initial framework	Exploration of data patterns revealed by field studies	Explicit conceptual basis and functional approach as preliminary hypothesis to be tested for connecting upstream drivers with downstream responses, including the accommodation of spatial discontinuities and diffusion effects
Drivers of change	A system of quality control to ensure all possible drivers of change are included	A system of quality control (e.g., exhaustive literature review) to ensure all possible drivers of change are included.
		Planimetric uncertainties and errors should be quantified where possible
Channel responses	A system of quality control to ensure all possible channel responses are included	A system of quality control to ensure that channel responses are comprehensively quantified.
		Planimetric and altimetric variables are at an appropriate resolution for the study objectives, and with errors quantified where possible
	Reach-differentiated analysis of channel changes	Reach-differentiated analysis of channel changes, ideally based on a comparative framework (e.g., paired catchment), with testing to validate inter-reach statistical differences, periodicities, structural variability or change point detection
Functional aspects of results	Development of a temporal synopsis and/or conceptual figure linking drivers for change and channel responses based on expert knowledge	Analytical framework for accommodating time-lagged responses and scaling effects that may not be obvious from observations. Synchronicity of causes and effect in time and space validated with tests
	Expert interpretation of potential cause-and-effect linkages, emphasizing synchronicity of causes and effect in time and concurrence of causes and effect in space	Ensure data are available for validating hypothesis in space (to detect potential lags and thresholds) and time (to detect different periods in driver and response domains).
		Establish and correlate temporal context for changes in terms of flood series, flow regime, or sediment regime. Where this is not possible, use rainfall series or data from a neighboring catchment.

Quality control	Expert interpretation	System of calibration and independent validation (could include methods based on sediment transport monitoring or sediment budget analysis)
Prediction, simulation, testing	None	Method for simulating reach responses without and with altered drivers for change (i.e., sensitivity analysis)
Conclusions	Judge the applicability of existing knowledge and concepts to the study results	Advance understanding of the synchronism between cause and effect or lag effects, validating preliminary hypotheses
	Identify potentially dominant factors, ideally in a conceptual cause-consequence chart.	Advance existing conceptual models and functional approaches of the cause-effect cascade. Where hypotheses are not validated, discuss failures and examine for additional causes as the basis for re-running the analyses.
	Identify priorities for hypothesis testing to confirm general applicability of results (ready to move to Proposed Future Studies column)	Prioritize focused research requirements using field research, physical or numerical modelling to add rigor to study findings, use focal channel network extents to add analytical detail related to cause-and-effect in space and/or time.

Table 4: Proposals for improving the rigor of cause and effect interpretations in cumulative impact studies in fluvial geomorphology

6. Prospects

6.1. River conservation and management

For river conservation, evidence suggests that river channels in industrialized nations are now more static, more entrenched and more regulated than in the recent past. This has significant interdisciplinary importance for those ecosystem services and attributes of biodiversity that rely on the natural functioning of flow, sediment and nutrient processes and the longitudinal and lateral connectivity of river channels with their floodplains. There is, for instance, a marked temporal coincidence between these changes and an estimated 81% reduction in abundance of freshwater aquatic populations since 1970 (WWF, 2016), resulting most commonly from direct and indirect 'habitat loss and degradation' (implicated in 48% of threat assessments across 449 populations of freshwater fishes, amphibians, reptiles, mammals and birds, WWF, 2016, their Fig. 13). Reductions in rates of lateral activity, increasing river incision, transformation of multi-thread channels into single thread, reduced sediment fluxes and bed sediment storage all imply simplification, impoverishment and absolute reductions in available river channel habitat. Such near-uniform simplification of river environments may represent another dimension in large-scale homogenization of river dynamics (e.g., Poff et al., 2007; Peipoch et al., 2015). The cumulative impact of multiple land-use changes and water resources development activities in the late twentieth century may have caused many river systems to cross a geomorphological 'tipping point' that is at least partially responsible for these enormous biodiversity losses. Better understanding these changes is especially critical in the context of the potential impacts of massive recent investments in hydropower dams (Zarfl et al., 2015) in regions such as the Amazon and Mekong basins (Finer and Jenkins, 2012; Kondolf et al., 2018).

There are multiple management implications of rivers operating as novel ecosystems, not least for concepts of 'naturalness' that underlie the goal of 'good ecological status' of surface waters under the 2000 EU Water Framework Directive (WFD) and the 'reference condition' assessments that underpin efforts at river restoration. Where river systems have evolved into morphologically-novel configurations, the ecological potential and health of such systems cannot be referenced to historic state variables and, more than ever, restoration must be conceived as an exercise in 'naturalization' (Rhoads et al., 1999), using process-based reference functions (Power et al., 1998) that provides targeted goals that work within the constraints of prevailing catchment drivers. Functionally, if altered 'hydromorphology' is critical to river ecosystem potential, as implied here, its evaluation should be an integral rather than optional part of WFD surface water assessments (Wharton and Gilvear, 2006), using dedicated assessments based on river function rather than from state variables derived from habitat assessment protocols (Belletti et al., 2015). Pre-project restoration planning must provide a good diagnosis of cause and effect, accommodate or rectify the cumulative impact of multiple activities, and collect sufficient baseline data to provide the basis for functional reference targets (e.g., Downs et al., 2011) against which to evaluate project sustainability (Downs and Kondolf, 2002; Piégay et al., 2016).

The scientific underpinning of river management in morphologically-novel ecosystems must reconcile the importance both of terrestrial sediment obtained from land-use changes and the changing processes and nature of network-derived sediment sources. The widespread existence of incised river channels implies changes in the predominant mechanism of bank retreat towards mass failures driven by bank-toe instability (e.g., Simon et al., 2000; Schottler et al., 2014) and, where upstream sediment sources are truncated by the existence of dams, the enhanced importance of sediment provision from downstream alluvial sediment stores, conceivably promoting further incision and channel widening (Downs et al., 2018). The apparent reduction in fluxes and storage of coarse channel bed sediment suggests fundamental changes in the dynamics of coarse sediment transport and a dwindling capacity for providing channel bed habitats. Coarse sediment should thus be treated as a finite resource in the provision of aquatic habitat and 'excess' fine sediment in channel bed habitats viewed as accentuating the imbalance in the ratio of increasing fine sediment to decreasing coarse sediment rather than simply the result of inadvisable land management practices. Where this occurs, gravel augmentation to increase coarse sediment storage on channel beds may be critical despite being a symptomatic rather than sustainable management measure. And, to the extent that restoration of degraded river ecosystems is most likely to be sustained where constraints can be removed, providing additional space for the river (Cals et al., 1998) as a 'fluvial territory' (Ollero, 2010) that allows for lateral channel adjustments (Piégay et al., 2005; Florsheim et al., 2008) will be critical.

6.2. Fluvial geomorphology

'No analogue' river channel forms, driven by novel process arrangements intimately linked to human drivers for change also prompt reflection on *how* geomorphological research is approached. Such research is logically focused at catchment and network spatial extents and with focal timescales from decades to a few centuries, largely commensurate with the Anthropocene as an industrial era phenomenon both technologically (Crutzen and Stoermer, 2000) and in terms of lowland floodplain modification (Lewin, 2013) and upland 'agro-industrial' alluvium (Foulds et al., 2013). Such a 'meso-scale', Anthropocene-focused, fluvial geomorphology should overlap productively with locally-focused process research and longer-term studies of landscape formation – and is perhaps most profoundly distinct because the role of human agency is integral to research. The approach should address questions about the relative impact of humans on geomorphological systems (e.g., as here, and see Brown et al., 2013, 2017) but also contribute to Crutzen's (2002, p. 23) "daunting task…for scientists and engineers to guide society towards environmentally sustainable management during the era of the Anthropocene" by providing more rigorous knowledge about the potential impacts of land-use changes and water resource management actions on sustainable approaches to river basin management.

Methodologically, Anthropocene geomorphology research could be based around three fundamental principles. First, to build on precedents from 'historical fluvial geomorphology' (e.g., Petts et al., 1989, and see Table 2) accentuated by the increasing availability of regionally-consistent datasets. Second, to integrate human actions in analysis such that fluvial systems are explicitly acknowledged to *co-evolve* with human activities (e.g., Chin et al., 2014, 2016; Harden, 2014; Troch et al., 2015) to different degrees. Third, the approach should seek to benefit from overlapping advances in geomorphology at landscape and process scales, utilizing shorter-term paleogeomorphology dating techniques to establish decadal-scale spatial changes and focused process studies to provide improved understanding of cause-and-effect, thus efficiently integrating holistic and reductionist strategies. Philosophically, the integration of human action requires a departure from classic scientific method, adopting instead aspects of a 'critical physical geography' and considering river systems as socio-biophysical landscapes (Lave et al., 2014; Tadaki et al., 2015; Blue and Brierley, 2016).

7. Conclusion

A systematic review of studies on the cumulative impacts of natural and human drivers on river channel evolution, drawn largely from industrialized nations, indicates that during the late twentieth century, river channels typically narrowed and incised, simplified their channel patterns, reduced their lateral activity rates and their fluxes and storage of bed sediments. Such rivers entered the twenty-first century more static, more entrenched and more regulated than at any previous point in recorded history, forming morphologically-novel ecosystems that may have contributed to the dramatic decline in freshwater aquatic biodiversity since about 1970 (WWF, 2016).

The reviewed studies represent expert judgement-driven case studies of cumulative impact analysis corresponding to a 'pattern discovery' phase of scientific endeavor and based on the availability of new data sets and technologies that permit an holistic (i.e., antireductionist) approach. Research generally results in summary evaluations depicted as site-specific conceptual models of river evolution (the 'pattern'). Statements on cause and effect usually derive from expert interpretation based on temporal synchronicity and spatial proximity and this may bias conclusions towards promoting local drivers for change rather than catchment-scale or atmospheric-scale drivers, or flood events as triggers (such issues are prevalent also in long-standing debates about arroyo incision in the US Southwest, e.g., Miller, 2017).

Because the reviewed studies focus on human drivers for change and lack mathematical or statistical 'proof' in evaluating cause and effect, they preclude a definitive statement regarding the existence of the Anthropocene in fluvial geomorphology according to the criterion of the 'overwhelming' impact of human activities (Steffen et al., 2007). However, if the criterion is relaxed to the 'significant capacity' for ecosystem engineering (Smith and Zerder, 2013), recent channel evolution appears to support existence of the 'Great Acceleration' in river system geomorphology (cf. Brown et al., 2013, 2017; Gibling, 2018). Reduced rates of change since about 1990 may reflect more responsible stewardship of the Earth system (as desired by Crutzen and Steffan, 2003) but seems more likely to reflect highly restrictive management practices that 'force' river systems to co-evolve directly with human activities. Overall, the study sample suggests a common trend towards over-exploiting river systems during the late twentieth century economic growth of industrialized nations with potentially significant consequences for ecosystem services.

Achieving more rigorous proof for the existence of a late-Anthropocene fluvial geomorphology requires cumulative impact research to move beyond case studies towards a hypothetic-deductive approach that includes developing long-term data depositories and shared methodologies. This would most likely be achieved using a best-practice model building approach that can accommodate the various data through explicit functional criteria including those for factors such as spatial and temporal discontinuity and diffusion and time lags. The approach must be amenable to internal calibration and independent validation.

Accommodating the implications of recent river system changes requires further emphasis on process-based approaches to river ecosystem management and restoration and, critically, reconceiving sediment cascades and budgets to reflect greater emphasis on network-related sediment processes that result from reduced longitudinal and lateral connectivity in river systems. In fluvial geomorphology, this may be best achieved through the development of an explicitly 'Anthropocene' strand to research in which human agency is integral and fluvial systems are explicitly and critically acknowledged to co-evolve with human activities. Such research would facilitate better knowledge about the relative influence of human drivers of change on river functioning in recent centuries, thus facilitating more sustainable approaches to river management and restoration that fulfil Crutzen and Steffan's (2003, p. 254-256) wish that, in the twenty-first century, the Anthropocene will become synonymous with responsible stewardship of the Earth System.

8. Acknowledgements

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